AquaHarmonics

Clean.Simple.Energy.

Control Co-Design of the AquaHarmonics Wave Energy Device

AquaHarmonics

Max Ginsburg

B.S. Electrical Engineering, OSU

Alex Hagmüller, PE

B.S. Mechanical Engineering, OSU

AquaHarmonics

Clean.Simple.Energy.

AquaHarmonics 1:20th scale device design methodology for the US DOE Wave Energy Prize:

- **Winning device based on highest HPQ:** $HPQ = ACE \cdot [I_{MF} \cdot I_{WC} \cdot I_{AP_{P2A}} \cdot I_{ES} \cdot I_{RS} \cdot I_{AC}]$
- **First look at ACE=Average Climate Capture Width Per Characteristic Capital Expenditure**
- **The ACE Metric is Comprised of Two Components**
  - **Average Climate Capture Width (ACCW)** = a measure of the effectiveness of a WEC at absorbing power from the incident wave energy field.
  - **Characteristic Capital Expenditure (CCE)** = a measure of the capital expenditure in commercial production of the load bearing device structure.

$$\mathbf{ACE} = \frac{\textit{ACCW} = (\textit{ P average absorbed (kW) / P resource (kW/m) })}{\textit{CCE} = \textit{RST} * A_{surf} * \rho * \textit{MMC}}$$

where:

RST = representative structural thickness [m]

A_{surf} = total structural surface area [m^2]

ρ = material density [kg/m^3]

MMC = manufactured material cost [US$/kg]

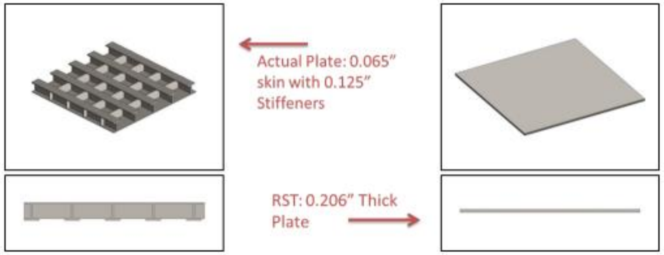


Figure 5. Visual representation of the *RST* concept for a component originally composed of plate and beams. All the material from the plate and beam structure (left) are distributed equally as a simple plate over the simplified surface area (right).

AquaHarmonics

Clean.Simple.Energy.

AquaHarmonics 1:20th scale device design methodology for the US DOE Wave Energy Prize:

- Winning device based on highest HPQ: $HPQ = ACE \cdot [I_{MF} \cdot I_{WC} \cdot I_{AP_{P2A}} \cdot I_{ES} \cdot I_{RS} \cdot I_{AC}]$
- By Inspection:
  - Greater average absorbed power yields larger ACE
    - More efficient devices, devices capturing energy in multiple DOF
  - Lower characteristic capital expenditure yields larger ACE
    - Smaller devices
    - Lower loads/less material

$$ACE = \frac{ACCW = (\, P\ average\ absorbed\ (kW) \,/\, P\ resource\ (kW/m)\,)}{CCE = RST * A_{surf} * \rho * MMC}$$

where:

RST = representative structural thickness [m]

A_{surf} = total structural surface area [m^2]

ρ = material density [kg/m^3]

MMC = manufactured material cost [US$/kg]

Table 3. *MMC* Values Used to Evaluate *CCE* for Each WEC in the Prize

Material	Low	Med	High
Steel - A36	$2,250	$3,000	$4,500
Steel Reinforced Concrete	$424	$510	$557
High-density Polyethylene (HDPE)	$6,000	$7,900	$12,000
Coated Fabric	$7,200	$9,500	$13,500
Aluminum - 5083	$4,900	$5,900	$8,000
Fiberglass (E-Glass/Epoxy)	$7,500	$8,200	$9,500
Filament Wound Fiberglass	$4,630	$5,510	$6,620

AquaHarmonics

Clean.Simple.Energy.

AquaHarmonics 1:20th scale device design methodology for the US DOE Wave Energy Prize:

- **The HPQ is Comprised of the following** $HPQ = ACE \cdot [I_{MF} \cdot I_{WC} \cdot I_{AP_{P2A}} \cdot I_{ES} \cdot I_{RS} \cdot I_{AC}]$
  - **Six hydrodynamic performance-related quantities will be determined through data processing for each device tested in the MASK Basin:**
  - One that measures the area swept by the device in its motions;
  - One that examines the maximum loads on the device's mooring;
  - One that measures the fluctuations in the devices absorbed power;
  - One that counts impact events;
  - One that quantifies the device's absorbed power in realistic seas; and,
  - One that examines the amount of energy used by the device for controls.

here the performance impact factors are defined as follows:

- I_{MF}, based on the statistical peak of the mooring force, accounting for mooring loads intensity
- I_{WC}, the statistical peak of the mooring watch circle, accounting for station keeping ability
- $I_{AP_{P2A}}$, the ratio of statistical peak-to-average of absorbed power, accounting for variability of the absorbed power
- I_{ES}, the number of end-stop impact events, accounting for frequency and severity of mechanical end-stop impacts
- I_{RS}, the absorbed power in realistic seas
- I_{AC}, accounting for the adaptive control effort.

Table 4. Impact Factors Used in the *HPQ* Weighting of *ACE*

HPQ Impact Factor	1	2	3	4	5
I_{MF}	0.92	0.96	1.0	1.04	1.08
I_{WC}	0.96	0.98	1.0	1.02	1.04
$I_{AP_{P2A}}$	0.92	0.96	1.0	1.04	1.08
I_{ES}	0.92	0.96	1.0	1.04	1.08
I_{RS}	0.90	0.95	1.0	1.05	1.1
I_{AC}	0.92	0.94	0.96	0.98	1.0

Design Decisions-Why a Point Absorber?

- We already had some prototypes for a point absorber
- Lots of literature available for point absorbers
  - Control
  - Hull types
  - Single body and multi body
- Appeared to be the most serviceable, potentially most simple topology for
  - Design
  - Installation
  - Manufacturability
  - Access to PTO
- Decided to proceed with point absorber for above reasons
- Has some drawbacks
  - Depending on mooring and PTO, may only extract power in 1 DOF (heave)
  - As a surface float, it will be in most energetic location in storms, on the ocean surface

AquaHarmonics

Clean.Simple.Energy.

<u>AquaHarmonics 1:20th scale device design methodology for the US DOE Wave Energy Prize:</u>

ACE Metric and HPQ Evaluation-Strategize to win!

- Assume that the ACE metric is a reasonable proxy for LCOE for device with low TRL
- Winning device must have highest ACE score, but HPQ is important as well
- HPQ factor can raise or lower the final score considerably-62% of ACE score at lowest and 144% of ACE score at highest
- Estimate HPQ performance based on design decisions
- Trade Offs exist within every unique design!

AquaHarmonics
Clean.Simple.Energy.

Literature review for Hull shape

Hull Selection

- Reviewed existing literature for hull of device; criteria included
    - Absorption ability, bandwidth
    - Manufacturability
    - Robustness

Selection:

- Selected a cone bottom with a 30 degree deadrise angle
- Highest bandwidth reviewed in sea states to be tested
- Good information available on structural ability/characteristics

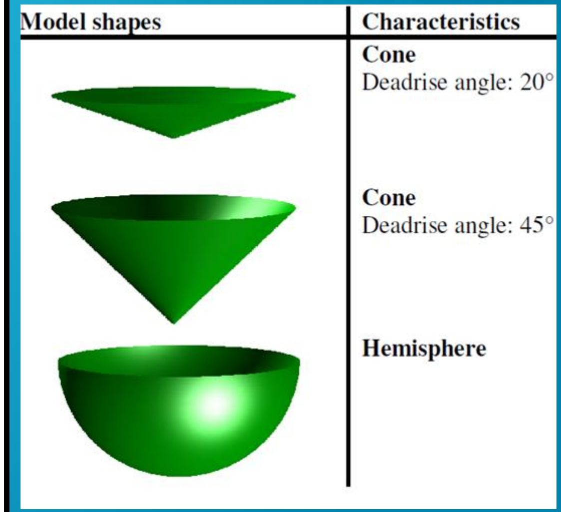
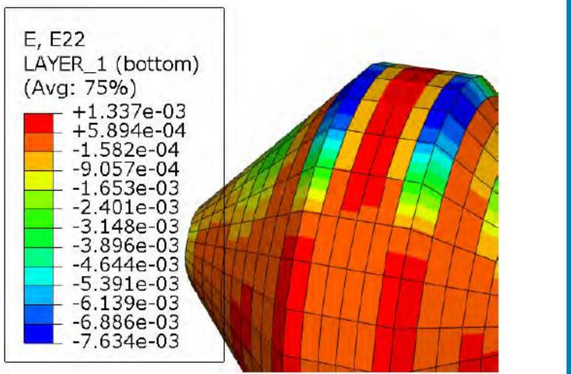


Figure 9-62 Lateral outdoor drop test from 4.8 meter; sequential images from the HSC measurements during impact of the BWOF.



Longitudinal strain distribution in the inner layer of the BWOF at 880 kN.

Literature review for Hull volume

Hull Size/Volume Selection

- Reviewed existing literature for maximum volume
  - First iteration started with ~900m^3 volume(full scale)
  - We want maximum power but only at maximum efficiency for high ACE score
  - Bigger devices make more power, but also have higher CCE (capital cost)
  - Based on ACE calculation, a very (infinitesimally) small would win WEP
    - Not really the point of the competition (but a fun thought!)

AquaHarmonics

Clean.Simple.Energy.

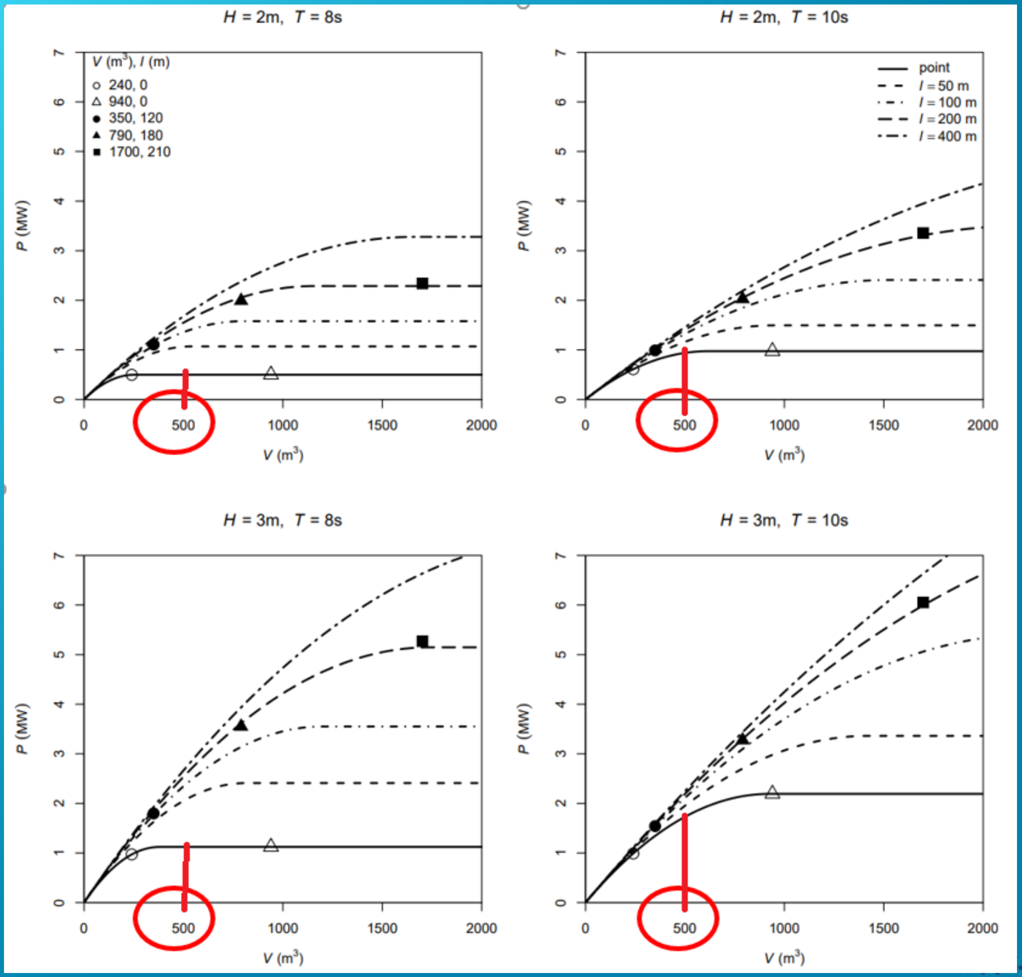
Hull Volume Selection:

Based on waves to be tested in WEP, peak efficiency for point absorber determined to be ~500 m^3(full scale) hull volume

Power Vs. Volume in various waves

WEP Waves

Wave Designation	T_P (s)	H_S (m)	Dir (deg)	s
IWS 1	7.31	2.34	10	none
IWS 2	9.86	2.64	0	none
IWS 3	11.52	5.36	-70	none
IWS 4	12.71	2.05	-10	none
IWS 5	15.23	5.84	0	none
IWS 6	16.50	3.25	0	none
LIWS 1	13.9	7.9	-30	3
LIWS 2	11.2	9.2	-70	7
RWS 1	14.38	1.52	-70	7
	7.18	2.16	0	10
RWS 2	14.83	1.59	-70	7
	8.65	1.30	-10	10



AquaHarmonics

Clean.Simple.Energy.

Literature review for control

- Reviewed existing literature for control of a point absorber
  - Many types have been researched: Damping only, Complex Conjugate, Latching, De-clutching, MPC….
  - Appears that tension only PTO's can make nearly the same power as a tension/compression PTO.
  - Simplifies structure of device and PTO, use of tensile materials where they are strongest.
  - By eliminating end stops in PTO, device can make use of full height of waves, non-linearities are eliminated, and maximum displacement at resonance can be utilized.

Case 1) No constraints on tether force ($F_t \in \mathbb{R}$) or power ($P \in \mathbb{R}$)

Case 2) Non-negative tether force ($F_t \in \mathbb{R}_{\geq 0}$), no power constraint ($P \in \mathbb{R}$)

Case 3) No constraints on tether force ($F_t \in \mathbb{R}$), non-negative power ($P \in \mathbb{R}_{\geq 0}$)

Case 4) Non-negative tether force ($F_t \in \mathbb{R}_{\geq 0}$), non-negative power ($P \in \mathbb{R}_{\geq 0}$)

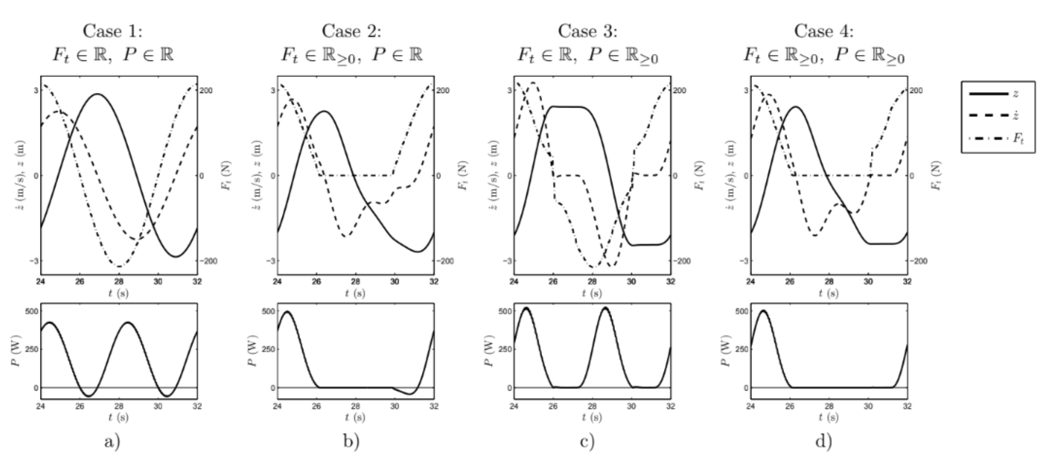
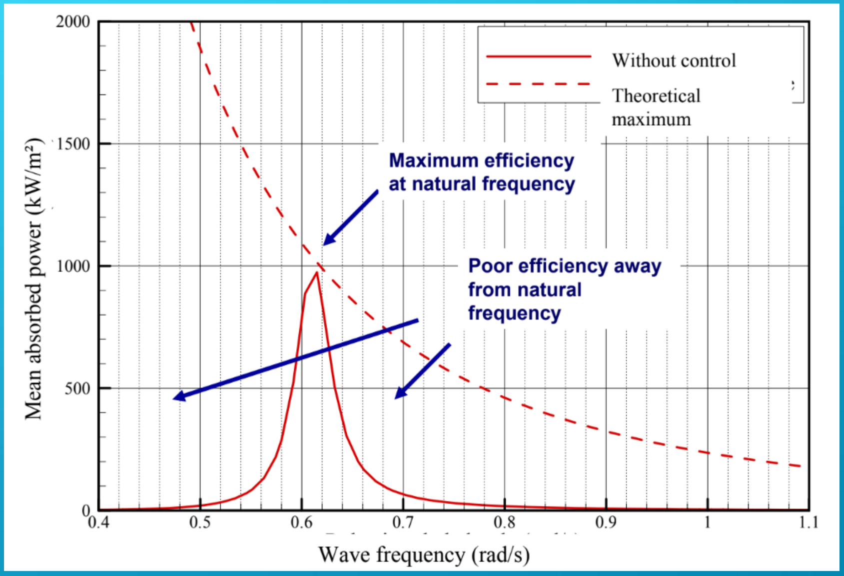
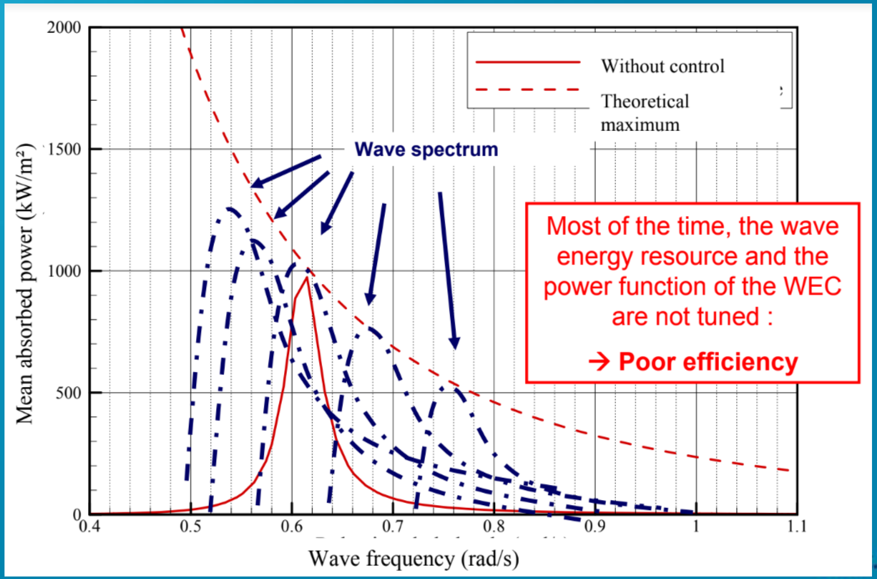


Figure 2: WEC optimal control results using DT for all four force/power constraint combinations.

Literature review for control

- Reviewed existing literature for control of a point absorber
  - Started looking at latching and de-clutching control
  - Ended with a modified PI control (complex conjugate)
  - Since device is lightweight and small, it has a high resonant frequency
  - Reactive power must be added to make device resonant for maximum power extraction
  - In storm conditions, spring term (Ki) can be removed to de-tune device motion for lower mooring loads
  - By use of pre-load in the system, the device always remains in tension with no slack mooring conditions



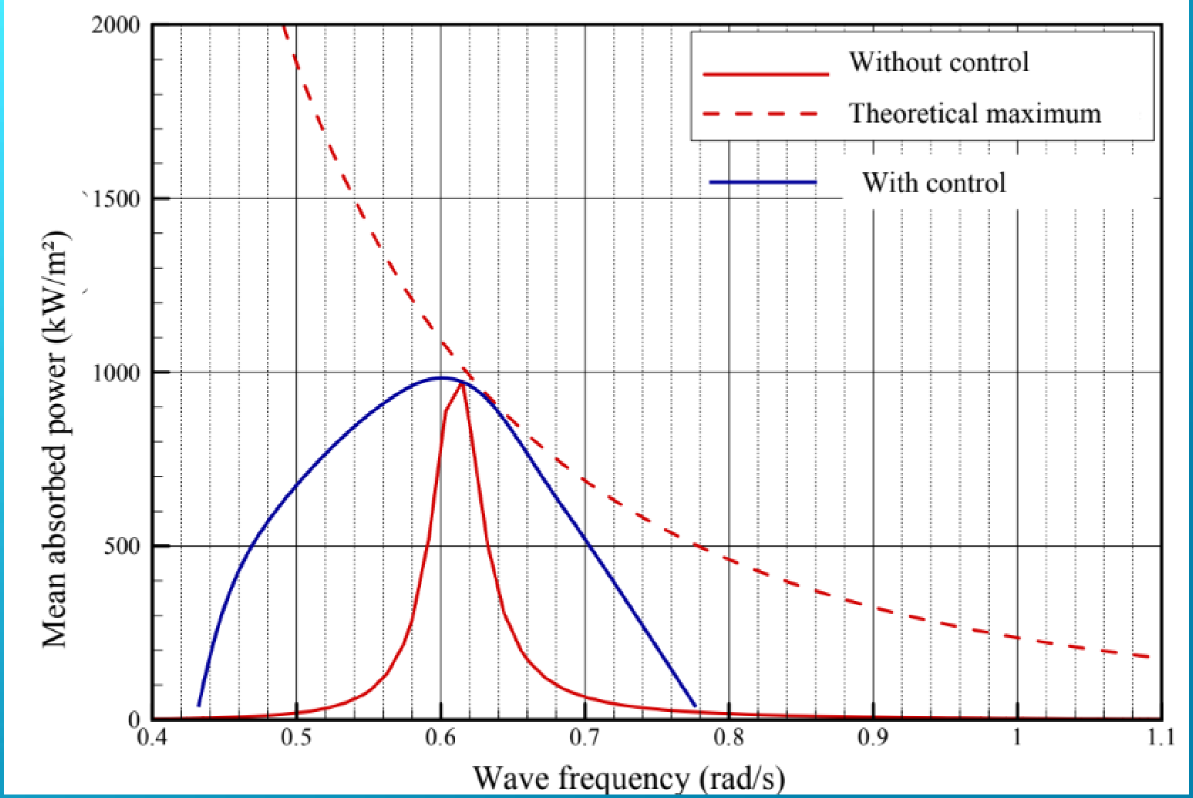


AquaHarmonics

Clean.Simple.Energy.

Literature review for control

- Reviewed existing literature for control of a point absorber
  - Concept broadens operational bandwidth in range of sea states (greater power absorption, impacts ACE positively)
  - Control concept has high peak to average loads (impacts HPQ score negatively)

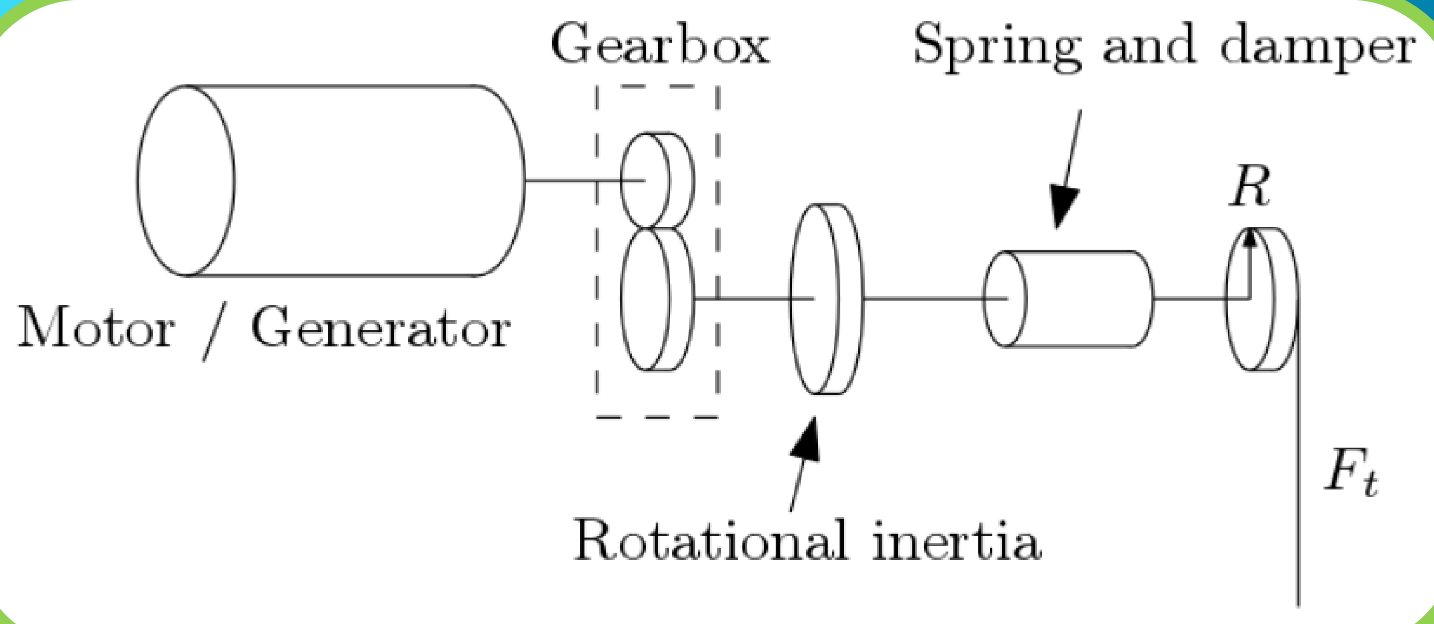


AquaHarmonics

Clean.Simple.Energy.

Selected PTO Topology

- Reviewed existing literature for control of a point absorber
  - Winch-Like PTO, tension only
  - Mechanical spring pre-load
  - Mechanically simple/robust, well known components, good topology for linear to rotational conversion
  - Allows for no end stops in operational conditions (simply add more line to the drum)



- **Revised HPQ estimate**
  - **Six hydrodynamic performance-related quantities will be determined through data processing for each device tested in the I**

$$HPQ = ACE \cdot [I_{MF} \cdot I_{WC} \cdot I_{AP_{P2A}} \cdot I_{ES} \cdot I_{RS} \cdot I_{AC}]$$

  - One that measures the area swept by the device in its motions;
    - **Anticipated small motions except heave**
  - One that examines the maximum loads on the device's mooring;
    - **Anticipated high peak to average, but no snap loads or end stops**
  - One that measures the fluctuations in the devices absorbed power;
  - One that counts impact events;
    - **Anticipated no impact events**
  - One that quantifies the device's absorbed power in realistic seas; and,
    - **Difficult to quantify at the time**
  - One that examines the amount of energy used by the device for controls.
    - **In terms of control effort, very low effort to apply controls (ie no geometric changes, only software)**

Table 4. Impact Factors Used in the *HPQ* Weighting of *ACE*

HPQ Impact Factor	1	2	3	4	5
I_{MF}	0.92	0.96	1.0	1.04	1.08
I_{WC}	0.96	0.98	1.0	1.02	1.04
$I_{AP_{P2A}}$	0.92	0.96	1.0	1.04	1.08
I_{ES}	0.92	0.96	1.0	1.04	1.08
I_{RS}	0.90	0.95	1.0	1.05	1.1
I_{AC}	0.92	0.94	0.96	0.98	1.0

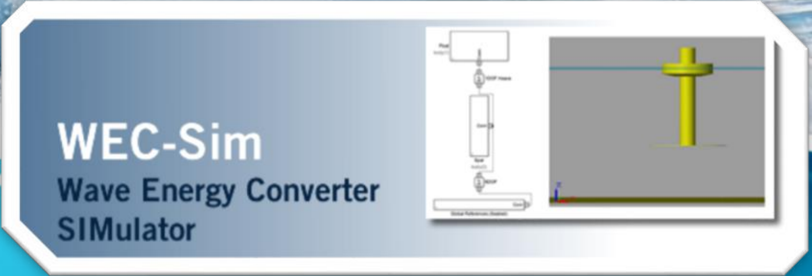
AquaHarmonics 1:20th scale device as tested in the Wave Energy Prize:

Final Device Topology

- Tension only Point Absorber, capture predominantly in heave
  - Trade capture in other DOF for simplicity in control and PTOs
  - Eliminate need for column loaded structures (ie, column loaded two body point absorber)
- Single body, Axi-symmetric cone-cylinder shaped hull
- ~500m^3 bounded volume
  - Aimed for maximum capture efficiency in WEP sea states
  - Control system should maximize power for selected size
- Winch-like direct drive power take off with mechanical spring energy storage
- PTO mooring line directly connected to seabed, 4 additional catenary mooring lines
- No end stop conditions in design states (only limited to line on PTO drum)
- Ability to de-tune device in storm conditions (minimize mooring line loads, device loads in energetic sea states)

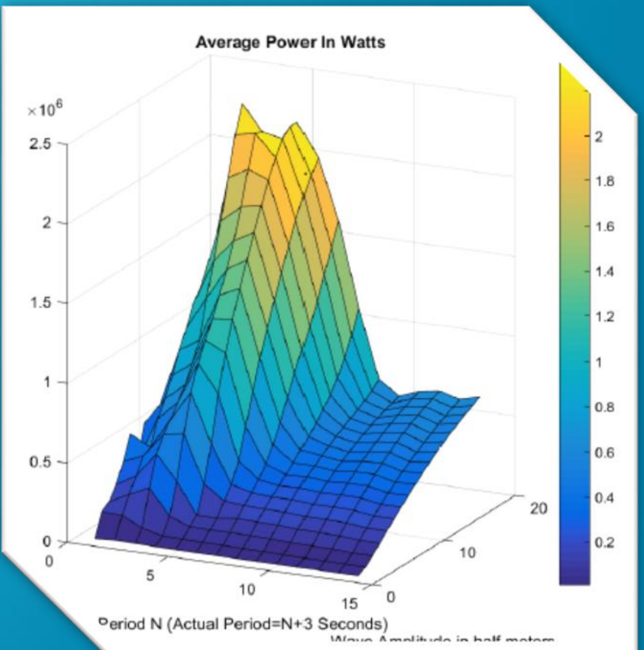
AquaHarmonics

Clean.Simple.Energy.

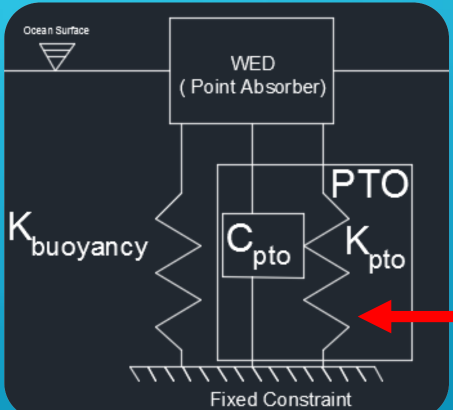


AquaHarmonics 1:20th scale design approach:

- Only 5 weeks to design, build and manufacture the device before tank testing
- Numerical analysis using WEC-Sim gave insight into design for selection of components (overestimated velocities for given power)
- Planned for ability to change mechanical spring rates and gear ratios quickly and easily
- Planned for a disciplined empirical approach



$$w_0 = \sqrt{\frac{k_{equivelent}}{m + m_a}}$$



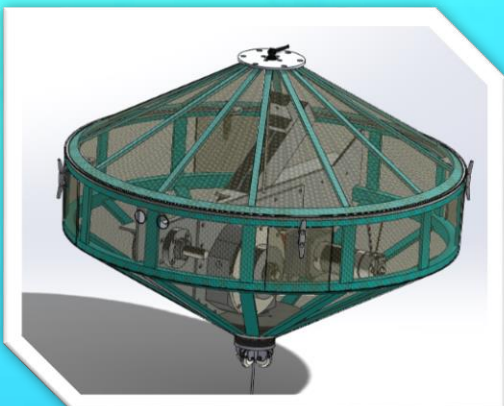
Springs in parallel!

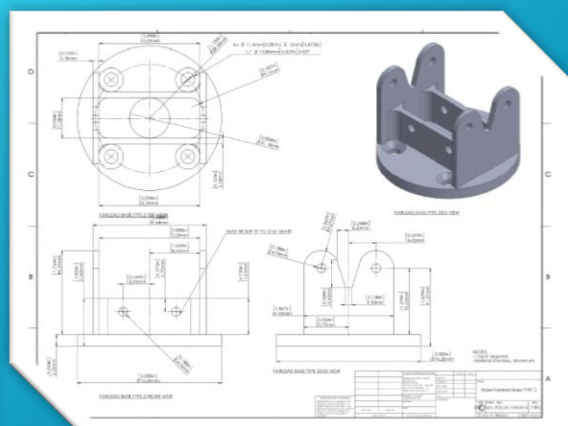
Negative Spring!

$$k_{equivelent} = k_{buoyancy} - k_{pto}$$

AquaHarmonics

Clean.Simple.Energy.



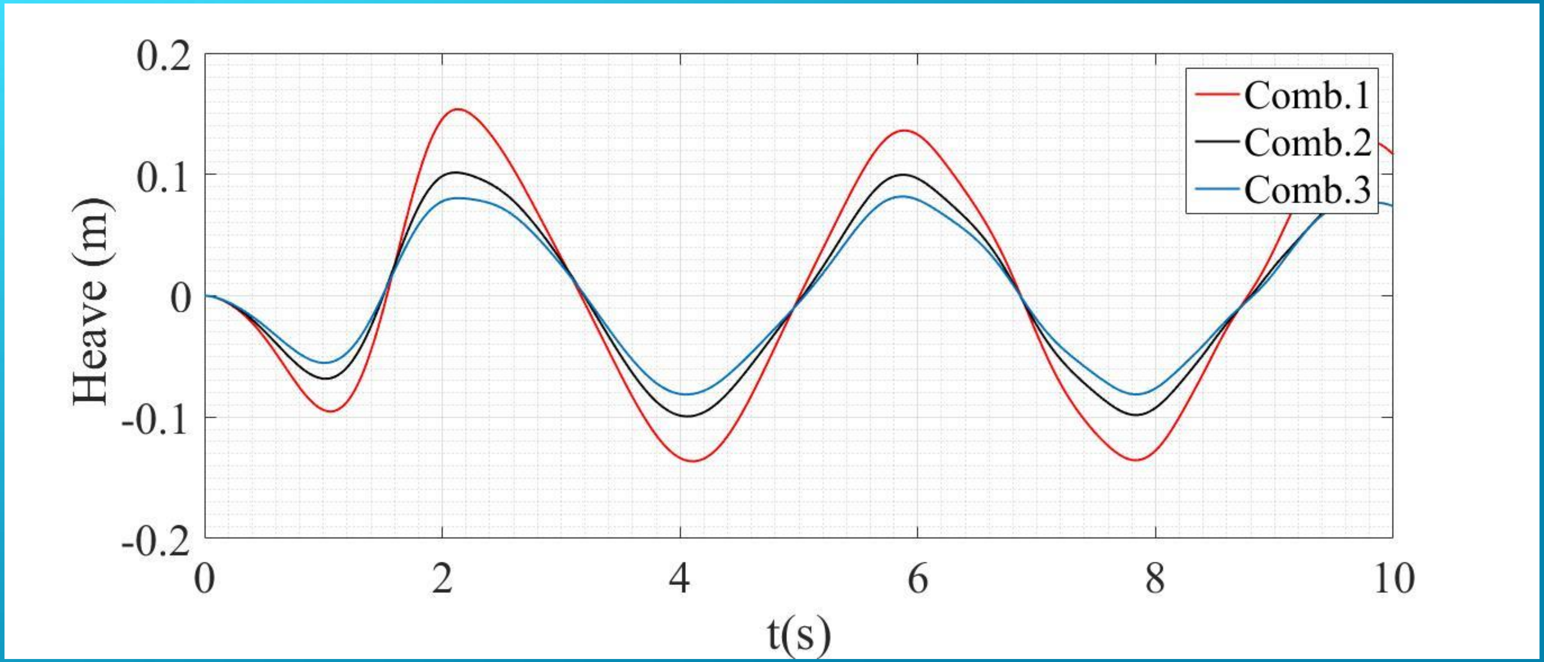


AquaHarmonics

Clean.Simple.Energy.

Simplifications, assumptions, procedures:

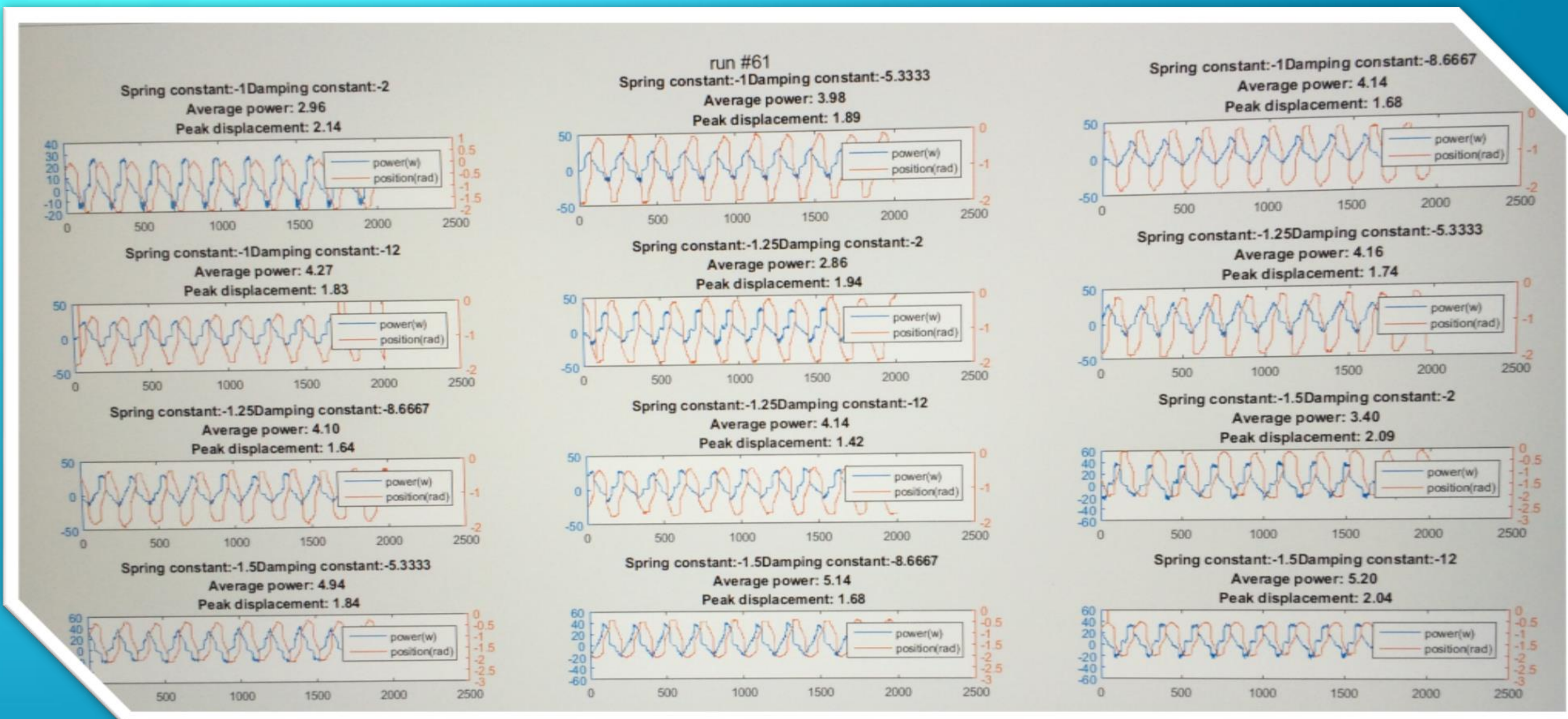
- Assume that regular wave performance is a proxy for irregular wave performance
- Started with only tuning spring rate to maximize displacement
- Once a negative spring parameter sweep gave the maximum displacement, then a parameter sweep for damping was conducted to determine maximum power
- Verification was conducted in irregular JONSWAP waves
- Parameter for negative spring and damp were selected based on optimal regular wave parameters for the same significant wave height and frequency



AquaHarmonics

Clean.Simple.Energy.

- Varied damping to maximize power
- Built a matrix of optimal parameters yielding max power in range of sea states



AquaHarmonics

Clean.Simple.Energy.

AquaHarmonics

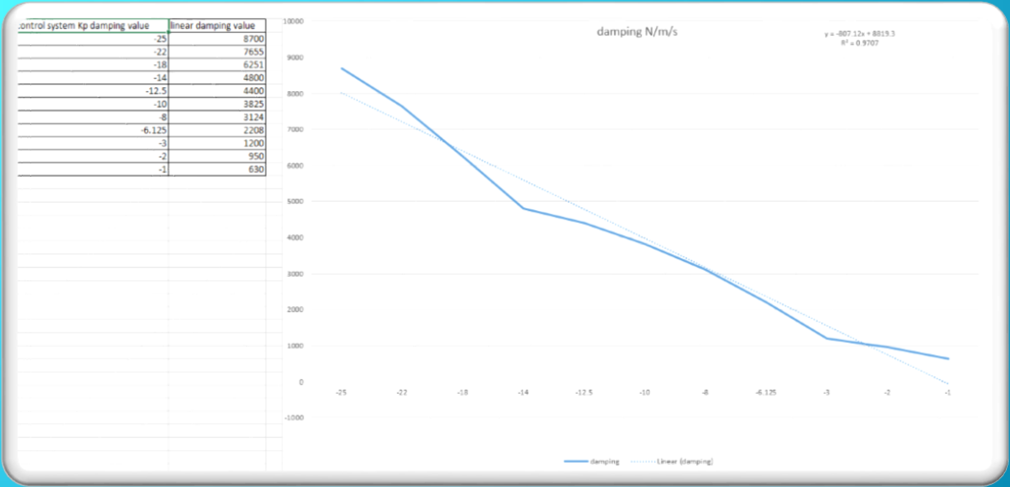
Clean.Simple.Energy.

AquaHarmonics

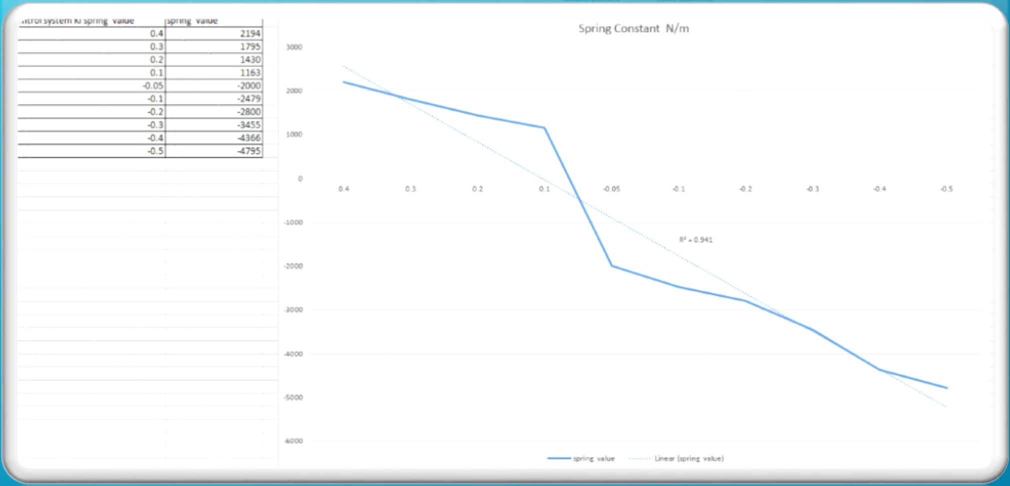
Clean.Simple.Energy.

~190 tests at OH Hinsdale Flume

- Determined range of spring and damping PTO is capable of
- Linear relationship between optimal Kp and Ki and wave frequency



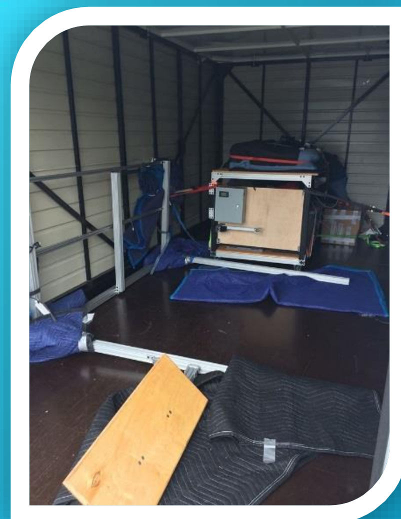
ontrol system Kp damping value	linear damping value
-25	8700
-22	7655
-18	6251
-14	4800
-12.5	4400
-10	3825
-8	3124
-6.125	2208
-3	1200
-2	950
-1	630

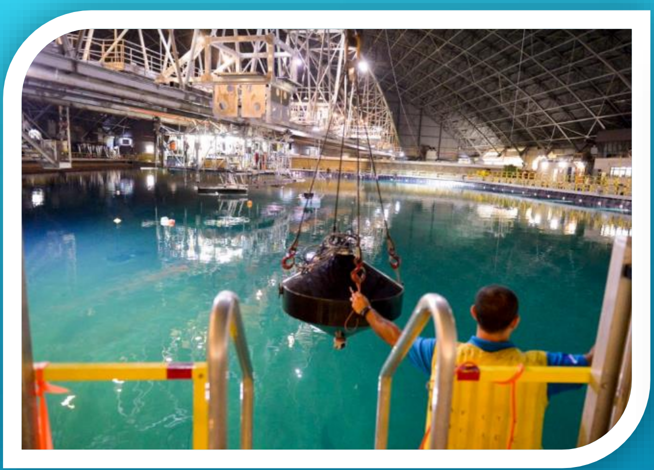


ntrol system Ki spring value	spring value
0.4	2194
0.3	1795
0.2	1430
0.1	1163
-0.05	-2000
-0.1	-2479
-0.2	-2800
-0.3	-3455
-0.4	-4366
-0.5	-4795

AquaHarmonics

Clean.Simple.Energy.





RESULTS!

ACE: 7.6m/million$

HPQ:7.4m/million$

<u>WINNING SCORE!</u>